INVESTIGATION OF THE TENDER ZONE IN THE COMPACTION OF COARSE-GRADED SUPERPAVE HOT MIX ASPHALT (HMA) MIXES

PAPER 03-2334

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July 24, 2002 Original Draft
November 12, 2002 Revised Draft

Submitted for Presentation and Publication at the 82nd Annual Meeting
Transportation Research Board
January 12 - 16, 2003
Washington, D.C.

<u>Word Count</u>

Manuscript:	6141
Tables:	3 @ 250 = 750
Figures:	2 @ 250 = 500
Total:	7391

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ABSTRACT

Tender hot mix asphalt (HMA) mixes have been observed and experienced by paving contractors for many years. However, during the field compaction of coarse-graded Superpave mixes, a "tender zone", not a true tender mix, is sometimes experienced. The tender zone is range of mix compaction temperatures during which the mix exhibits instability during roller action. There have been many possible causes of the tender zone presented including differences in lab and production absorption, mix moisture, low dust to asphalt ratio, increased asphalt binder film thickness, and a temperature differential with the lift.

A study was conducted to document and evaluate field mixes exhibiting the tender zone to determine the possible cause(s) for its occurrence. Documentation included mix, production, and construction related items. Laboratory evaluation consisted of mix gradation and volumetric testing along with Superpave asphalt binder testing on the project asphalt binder before and after steam distillation. Project results failed to clearly identify one particular reason for the tender zone occurrence. However, it is felt that the tender zone was a result of field absorption being less than design and increased asphalt binder film thickness acting in conjunction with an inherent temperature differential within the lift.

Key Words: Tender Zone, Superpave, Steam Distillation

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INTRODUCTION AND PROBLEM STATEMENT

The compaction of coarse-graded Superpave designed mixtures can be difficult due to the occurrence of a "tender zone". The tender zone is defined as a range of mix compaction temperatures during which the mix exhibits instability during roller action.

Tender mixes have been observed and experienced by paving contractors for many years. There are many possible mixture characteristics that may lead to tenderness during field compaction. Among these is the use of an excessive amount of rounded fine aggregates (natural sands), a low viscosity asphalt binder, a high asphalt binder content, a high fine aggregate percentage, a low filler content, internal moisture in the aggregate, etc. (*1, 2, 3*). All of the above-mentioned characteristics can alone, or in combination, cause a mix to exhibit tender behavior. However, with coarse-graded Superpave mixes, the tenderness occurs within a range of mix compaction temperatures (tender zone) not throughout compaction.

Some of the possible causes of the tender zone include the following:

1. Mix Design Asphalt Binder Absorption Different Than Production Absorption

Superpave mixtures are short-term aged to simulate the aging and absorption during production, transport, and laydown. The short-term aging period generally allows adequate time for the full amount of asphalt binder absorption by the aggregates.

In many cases the amount of binder absorption during the design procedure is greater than the absorption experienced during production, transport, and laydown. For instance, if a given mixture was aged for a four-hour period at 135°C, but the project was only 10 minutes from the asphalt plant (with no storage time), the mixture would exhibit different properties than during mix design. A potential result of this short production/transport/laydown time is that the field binder absorption may be less than the mix design binder absorption. In this case, the effective asphalt binder volume in the mix during compaction is increased; yielding an over-asphalted mix prone to tenderness.

2. Aggregate Internal Moisture

In an ideal case the aggregate internal moisture would be zero. However, this is seldom the case. During production, placement, and compaction, the aggregate internal moisture will attempt to escape due to elevated temperatures. Similar to asphalt binder, the escaping moisture can act as a mixture lubricate by lowering the apparent viscosity of the asphalt binder. Additionally, it is possible that the moisture may prevent the asphalt binder from absorbing into the aggregate, yielding too high an effective asphalt binder content.

3. Low Dust to Effective Asphalt Ratio

The original Superpave dust to effective asphalt (D/A) ratio criteria ranged from 0.6 to 1.2. AASHTO has increased the upper limit to 1.6 for coarse-graded Superpave mixtures to allow for more dust to increase the mix viscosity. A given coarse-graded mixture with a low ratio will likely exhibit a lower mixture viscosity than a mixture with a high ratio. The lower viscosity mixture may be more likely to exhibit tenderness during compaction than a high viscosity mix. However, it should be noted that the overall aggregate blend gradation and filler properties greatly influence mix behavior.

4. Increased Asphalt Binder Film Thickness and Temperature Differential in the Lift

The increased asphalt binder film thickness of coarse-graded Superpave mixtures, along with the presence of a temperature differential within the lift may result in tender mix behavior. With coarse-graded mixtures, the total aggregate surface area is reduced, yielding increased asphalt binder film thicknesses. Even at lower asphalt contents, the film thicknesses of coarse-graded mixes can be substantially higher than fine-graded mixes.

During compaction the increased film thickness and the temperature differential within the lift can act together to cause mix tenderness. At the outset of breakdown rolling the amount of aggregate interlock is minimal and the mix temperature is hot (small temperature differential) throughout the lift. As breakdown rolling continues, the top and bottom portion of the lift become cooler than the middle portion. The top and bottom of the lift now have a greater mix viscosity than the middle portion. The top portion is now viscous enough to push, as a "cooled" mass, in front of the roller and slip along the hotter (less viscous) middle portion of the lift.

Figure 1 shows the temperature at various locations within a constructed pavement lift. In this example a 25-mm lift being placed with the temperature determined at the surface and bottom of the lift and at the 6-mm and 15-mm locations within the lift. (*4*) A similar temperature differential relationship could be assumed to occur in Superpave mixes with varying lift thicknesses. As mentioned previously, the tender zone tends to occur when breakdown rolling is nearing completion, generally corresponding to approximately 5 to 10 minutes after the initial mix placement. From Figure 1, the temperature at the surface and bottom of the lift at these times is approximately 85°C; however, in the middle of the lift the temperature is substantially hotter, approximately 107°C. At this point the middle portion of the lift is less viscous than the top and bottom of the lift.

The horizontal force component of a steel wheel roller will tend to push the higher viscosity (cooler) top portion of the lift past the lower viscosity (hotter) middle portion of the lift, as shown in Figure 2, causing shoving, checking, and lateral movement. Some success has been obtained by using pneumatic rollers for intermediate compaction, opposed to steel wheeled rollers. The kneading action of pneumatic rollers acts to restrain the mat from lateral movement more so than steel wheel rollers.

As the temperature of the middle portion of the lift decreases, its viscosity increases to a point were shearing and tenderness decreases. However, the mix is still hot enough that a small amount of compaction (8 to 16 kg/m^3) with the finish roller can be obtained. In some cases, density has been obtained at surface pavement temperatures down to approximately 49°C. Obviously, the amount of temperature differential and the cooling rate are dependent upon the weather conditions, the lift thickness, and the overall mix temperature.

OBJECTIVE

The objective of the study was to collect information concerning the production and placement of HMA pavements experiencing problems with the tender zone. Additionally, samples of produced mix and asphalt binder were collected and laboratory testing performed. The project information and laboratory test results were analyzed to determine a cause(s) and offer a possible solution(s) to the tender zone.

SCOPE AND TEST PLAN

Five HMA construction projects were evaluated in the study. The project was divided into two parts: Documentation and Evaluation.

Documentation

Documentation of the production, transport, and laydown operations was conducted. Among the items documented were the job mix formula, plant information, roadway data, weather conditions, paving equipment, compaction methods (rolling patterns), and specific information pertaining to the tender zone.

Evaluation

The laboratory evaluation consisted of asphalt content, aggregate gradation, and mixture volumetric testing (theoretical maximum density and bulk specific gravity). The asphalt content was determined by use of the ignition furnace or by solvent extraction, with the aggregate gradation determined on the remaining sample.

Additionally, asphalt binder samples were obtained from each project, with which, Superpave binder testing (verification of the performance grade) and steam distillation testing were conducted. Superpave binder testing was performed on the original and steam distilled samples.

Laboratory test results that may attribute to the occurrence of the tender zone are excess asphalt content and/or a low amount of minus 75 μm material (resulting in a low D/A ratio and a possible reduction in mix viscosity), and mixture volumetric properties (air voids, voids in the mineral aggregate, and voids filled with asphalt).

The mix $N_{initial}$ density was reviewed to determine whether a mixture showed any tendency toward tenderness during lab compaction. $N_{initial}$ density for coarse-graded mixtures is normally well below the maximum specified density of 89 percent of G_{mm}. If compacted samples show a high density at $N_{initial}$, this may indicate a change in the mix parameters from those at design. Among the items that may result in a higher $N_{initial}$ density from the design value are a high asphalt content, low filler content, and aggregate moisture.

SITE REPORTS AND PRESENTATION OF RESULTS

Brief site reports from each evaluated project are included in the following sections. The site reports include general project information, mix descriptions, construction procedures, and a description of the mix tenderness. Along with each site report, the mixture information (asphalt content, gradation, volumetrics, and film thickness) is presented and analyzed to determine if there are possible reason(s) for the tender zone in each respective project.

Alabama (Highway 157)

General Project Information

The project consisted of a 50-mm overlay of an asphalt pavement on the southbound travel lane of Highway 157 approximately 8 kilometers north of Moulton. Weather conditions were 21°C, sunny, with a 16-kph wind.

Mix Description

The mix consisted of a 12.5 mm nominal maximum size coarse-graded limestone/sand/slag blend designed at 106 gyrations (N_{design}) resulting in a design asphalt content of 4.9 percent. The binder used was a PG 67-22 (unmodified). No anti-stripping agent was used in the mix. Complete project information for this, and all projects, is found in Table 1.

Construction Information

The project was located approximately 8 kilometers (7 minutes haul time) from the drum plant. No significant mix storage was observed at the plant. Tandem trucks fed the mix to a Roadtec RP30 paver. Breakdown rolling was conducted using a Caterpillar CB634C roller starting immediately behind the paver at a surface temperature ranging from 140 to 143°C. Two passes in maximum amplitude and frequency were used for breakdown rolling. The average surface temperature at the completion of the breakdown rolling was approximately 116°C. No intermediate rolling was performed due to mix movement in a surface temperature range from approximately 116 down to 57°C. The contractor did not use a pneumatic roller in the tender zone due to concerns about material pick-up. Finish rolling began at approximately 57°C and was performed using a Hypac C764B roller operating in static mode, making two to three passes primary to remove roller marks. An increase in density of 8 to 16 kg/m^3 was usually observed with the finish rolling.

Mix Tenderness Description

Tenderness was observed at approximately 116°C, which corresponded to the latter part of the breakdown rolling. A small amount of lateral movement and pushing was observed, although not to a large degree, but did increase as the pavement surface temperature decreased. The contractor stated that the degree of the tenderness seemed to change daily.

Alabama (Highway 78)

General Project Information

This project was visited while production had been stopped due to construction problems. This night paving project consisted of a 63-mm overlay of an asphalt pavement on the southbound lanes of Highway 78 near Jasper.

Mix Description

The mix consisted of a 19.0 mm nominal maximum size coarse-graded limestone blend with 15 percent reclaimed asphalt pavement (RAP) designed at an N_{design} of 100 gyrations. The design asphalt content was 4.5 percent. The binder used was a PG 76-22 modified originally with Styrene Butadiene Rubber (SBR) and later with Styrene Butadiene Styrene (SBS). No anti-stripping agent was used in the mix.

The underlying pavement was severely cracked with full depth cracks down to the cement treated base material some 250-mm below. As evidenced by water stains on the existing pavement adjacent to cracks, it appeared that water had seeped from the cracks onto the surface.

During construction the contractor routinely experienced a problem with the mix losing approximately 2 to 3 percent density after the breakdown rolling had been completed. This density loss was documented by nuclear density testing and typically occurred at a surface temperature below 113 to 118°C. According to the contractor, the mix seemed to slightly increase in volume (swell) at various locations resulting in de-compaction. This increase in volume (swelling) and de-compaction was not constant over the project, which resulted in substantial roughness. Prior to overlaying, portions of the most severely cracked existing pavement had been patched to a depth of 100 to 150-mm. Swelling and de-compaction were not observed in these patched areas. This along with the water stains on the surface indicated that the swelling was likely caused by water in the underlying pavement structure being brought to the surface during construction. After reaching the bottom of the placed asphalt mix, the water turned to steam, greatly increasing in volume, resulting in de-compaction of the overlying mix. The water in the pavement structure was likely a result of very significant rainfall during the two or three weeks immediately prior to construction.

There was also a theory of water from the rollers causing mix tenderness. If that were the case for this project the problem would have been observed on the entire project, not just in the non-patched areas.

As mentioned previously, there were two asphalt modifiers used on the job: SBR and SBS. SBR was originally used and then SBS to see whether the modifier type would decrease the tenderness. The contractor reported no significant difference in mix behavior between the two modifiers.

A RS-1 emulsion was used for the tack coat, which was of concern since the project was being completed at night; however, the contractor reported that the emulsion had clearly broken prior to placement of the overlay.

Florida (Interstate 10)

General Project Information

The project consisted of an intermediate 50-mm lift placed over a rubblized concrete pavement. During the evaluation, the contractor was paving the shoulder of westbound Interstate 10 approximately 8 kilometers east of Marianna. During the evaluation the weather conditions were 32 to 35°C, sunny, with a slight wind.

Mix Description

The mix consisted of a 12.5 mm nominal maximum size coarse-graded 100 percent limestone blend (80 percent Alabama limestone and 20 percent local limestone screenings) designed at an N_{design} of 96 gyrations, resulting in a design asphalt content of 6.5 percent. The binder used was an AC-30 (unmodified). The binder manufacturer added a liquid anti-stripping agent at 0.75 percent by total weight of the asphalt binder.

Construction Information

The haul distance from the drum plant to the project was approximately 11 kilometers (10 minutes). There was a minimal amount of mix storage at the plant; however, there were several instances where the mix remained in the truck for approximately 30 minutes after arriving at the site.

A combination of conventional end dump trucks and horizontal flow trailers delivered the mix to a Blaw Knox PF3200 paver. The average surface temperature behind the paver ranged from 135 to 143°C. An Ingersoll Rand DD130, operating in maximum amplitude and frequency, was used for breakdown rolling and followed between 6 and 9 meters behind the paver. The rolling pattern observed was one pass toward the paver on the inside edge, then back along the same line, another pass up along the opposite edge and then back along the same line. The contractor reported frequently changing the rolling pattern to achieve density throughout the project. The average surface temperature at the completion of the breakdown rolling was approximately 107°C. At that time, an Ingersoll Rand DD110 roller began the intermediate rolling utilizing the same rolling pattern as the breakdown roller. Intermediate rolling continued down to approximately 88°C. During breakdown and intermediate rolling the mix showed no instability under the roller. However, at approximately 88°C surface temperature, the mix began to move laterally and push substantially in front of the roller.

At approximately 57 to 63°C surface temperature finish rolling began with a Caterpillar CB634C roller operating in static mode. The rolling pattern varied, but generally matched the patterns used by the intermediate roller. Throughout the project, an increase in density of 16 to 32 kg/m^3 was achieved with the finish roller.

Mix Tenderness Description

Tenderness was observed during the latter part of the intermediate rolling at approximately 88°C surface temperature. Any further rolling from approximately 88 to 63°C resulted in the mix moving substantially and a density decrease. A pneumatic roller was not used by the contractor for compaction within the tender zone, primarily due to material pick-up concerns.

Florida (Highway 301)

General Project Information

The project consisted of a 50-mm overlay of an asphalt pavement on the passing lane of southbound Highway 301 near Hawthorne. Weather conditions were 29 to 32°C, sunny, with no wind.

Mix Description

Similar to the Florida Interstate 10 project, the mix consisted of a 12.5 mm nominal maximum size coarse-graded limestone blend designed at an N_{design} of 96 gyrations resulting in a design asphalt content of 7.0 percent. Twenty percent RAP was used in the mix. The binder used was an AC-30. The binder manufacturer added a liquid anti-stripping agent at 0.75 percent by total weight of the asphalt binder. An RS-1 emulsion was used as the tack coat.

Construction Information

The haul distance from the drum plant to the project was approximately 15 kilometers (15 minutes). There was no mix storage at the plant and only a minimal amount of wait time at the roadway. Horizontal flow trailers delivered the mix to a Blaw Knox PF3200 paver. The average mix surface temperature behind the paver ranged from 141 to 146°C. An Ingersoll Rand DD110 was used for breakdown rolling and followed closely behind the paver. All the breakdown rolling was completed using maximum amplitude and frequency, with the rolling pattern consisting of one pass up the right edge and then back along the same line. The pattern was duplicated along the left edge with a final pass made up the middle of the lane. Average surface temperatures after breakdown rolling were 107 to 113°C. At this point intermediate rolling began with another Ingersoll Rand DD110 using the same rolling pattern and settings as the breakdown roller. Intermediate rolling continued down to approximately 88°C surface temperature, where the mix began to exhibit tenderness.

The mix was allowed to cool down to approximately 57 to 60°C surface temperature before finish rolling started. A Hypac C778B roller was used and made sufficient passes to remove the roller marks from the pavement.

Mix Tenderness Description

Tenderness was first observed at about 88°C surface temperature. From this temperature down to 60°C surface temperature, the mix exhibited substantial lateral movement and pushing in front of the roller. No tenderness was observed outside the 60 to 88°C temperature range.

Mississippi (Highway 49)

General Project Information

The project consisted of a 50-mm overlay of an existing asphalt and concrete pavement located in the travel lane of northbound U.S. Highway 49 near Mount Olive. Weather conditions were approximately 27°C, sunny, with a slight wind.

Mix Description

The mix consisted of a 12.5 mm nominal maximum size coarse-graded blend designed at an N_{design} of 96 gyrations resulting in a design asphalt content of 6.2 percent. Aggregates used in the blend consisted of 80 percent pit run crushed gravel, 9 percent sand, and 1 percent hydrated lime, along with 10 percent RAP. The asphalt binder was a PG 76-22 modified with a SBS modifier. In addition to the hydrated lime, a liquid anti-stripping agent was added by the manufacturer at a rate of 1.5 percent of the total weight of the asphalt binder. During design, the mix was short-term aged for 1.5 hours at the compaction temperature of 149°C.

Construction Information

The mix was produced approximately 5 kilometers (5 minute haul time) from the project site. Mix storage at the drum plant was minimal during the project. The contractor utilized a windrow paving technique, with horizontal flow trailers and end dump trucks used in conjunction with a Crafco Accupave windrow device to construct the windrow. A Caterpillar WE601B windrow elevator fed a Caterpillar AP1000 paver. A RS-1 emulsion was used as the tack coat. The average mix surface temperature behind the paver was 146°C. The breakdown roller, an Ingersoll Rand DD130, followed immediately behind the paver. The contractor had varied the amplitude and frequency of the roller throughout the project to optimize compaction, but reported medium amplitude and high frequency yielded the best results. The typical breakdown rolling pattern used was one pass up on the outside edge, back along the outside edge, another pass up along the opposite edge, and then back along the same line. Because of the occurrence the tender zone, no intermediate roller was used. A Hypac C778B roller was used for finish rolling with no set pattern. Two to three passes were typically made in static mode at a surface temperature of approximately 66°C. If the density could not be increased, the contractor reported that vibration by the finish roller was used at the same temperature. An increase in density was observed when vibrating at surface temperatures above 66°C, but below 66°C the contractor reported a decrease in density. Some noticeable breakdown of material was observed when vibration was used with the finish roller.

Mix Tenderness Description

From the beginning of breakdown rolling at approximately 146°C surface temperature down to approximately 118°C, there appeared to be no tenderness. However, below approximately 118°C, the mix began to push laterally and in front of the roller. The degree of movement increased as the surface temperature decreased and as the ambient temperature increased. The contractor reported that the same scenario had been seen throughout construction. At approximately 66 to 71°C, the tenderness in the mix decreased and the contractor was able to conduct finish rolling. No attempts were made to use a pneumatic roller in the tender zone, due primarily to the contractor’s past experience with material pick up.

A portion of the underlying layer was concrete, which seemed to increase the magnitude of the tenderness. As mentioned previously, the mix for the travel and passing lanes was the same, but a modified asphalt binder was used in the travel lane. The contractor reported that the tenderness was less when using the modified asphalt.

Laboratory Testing Results

Mixture Results

Samples of the produced mix were obtained from each project for lab testing. Table 2 shows the design and production values of gradation, asphalt content, voids in mineral aggregate (VMA), air voids, voids filled with asphalt (VFA), percent G_{mm} at $N_{initial}$, film thickness, and dust to effective asphalt ratio. (Note: All obtained samples had to be reheated for lab compaction, so the resulting volumetric property values may be slightly different from that of mixes that were not reheated.)

From Table 2, all the projects had asphalt contents within 0.3 percent of the job mix formula. This indicates that excessive total asphalt contents were probably not the cause of the observed tenderness. For all projects, except the Alabama Highway 157 job, the calculated VMA was within 0.7 percent of design. The Alabama Highway 157 project showed an increase of 1.7 percent VMA, which is a result of the 6.4 percent air voids. Air voids for the remaining projects also increased slightly from 0.3 to 1.3 percent above the design, which may be the result of re-heating. Values of percent G_{mm} at $N_{initial}$ for all the projects were well below the 89 percent maximum value, both during design and production.

All of the projects had increases in the percent passing the 0.075 mm sieve from design to production. This increase in the dust led to production D/A ratios being higher than design values.

Film thicknesses ranged from 8.9 to 12.8 microns for the design mixes. These film thicknesses are high primarily due to the low dust content and the overall aggregate blend coarseness. During production, the film thicknesses mostly decreased, primarily as a result of the increased dust content.

Asphalt Binder Test Results

The asphalt binder from four of the five projects was evaluated using the Superpave binder testing procedures. (Binder was unavailable from the Alabama Highway 78 project.) The binder was graded using Superpave asphalt binder testing protocols in the as-received condition and after steam distillation.

Steam distillation was conducted because the Superpave asphalt binder grading system does not directly identify asphalt binders that may have excessive light ends present. In some cases, a low viscosity asphalt binder (more light ends present) may be used to obtain the necessary Superpave low temperature grading, then modified to achieve the high temperature grading. During production, these light ends can possibly be released causing the mix to exhibit over-asphalted mix characteristics. Some believe that the steam distillation procedure better represents the production conditions during production in a drum plant than does the thin film oven-conditioning test. (5) It should be noted that current laboratory short term asphalt binder aging is conducted with the rolling thin film oven test, which may better represent field short term asphalt binder aging.

The steam distillation procedure used consisted of placing a sample of the obtained asphalt binder in a volumetric flask and gradually applying heat. Generated steam was diffused through the asphalt binder sample. The viscosity or stiffness of an asphalt binder with light ends present should increase after the completion of the steam stripping procedure.

The results of the asphalt binder testing before and after steam stripping are shown in Table 3. It appears that there is generally only a slight increase in the viscosity of each binder evaluated after the steam stripping procedure. This would tend to point to the fact that there were few, if any, light ends present in the binders. However, the data are too little to accurately determine the effect of possible light ends on the tenderness behavior of the observed mixes. More in-depth research should be conducted to determine whether light ends attribute to tender mix behavior.

OBSERVATIONS

Each paving project in which the tender zone occurs has its own set of weather, mix, and construction characteristics, making the determination of the causes for the tender zone an extremely difficult task. The purpose of this study was to document projects in which the tender zone occurred to determine possible causes for its occurrence.

The tender zone generally occurred at approximately 110°C down to 60°C. It does not appear from the gradation, volumetric, or asphalt binder test results that any mix parameter can be singled out as directly causing the tender zone.

Based upon the observations during construction, two primary causes are provided as possible reasons for the occurrence of mix tenderness in the five projects. First, a common characteristic in four of the five projects visited (AL 157, FL I-10, FL 301, and MS 49) was very short haul times and very little mix storage time. Construction observations for these four projects indicated that each had haul times less than 15 minutes with little or no storage time. The percent absorbed binder during mix design for these four projects ranged from 0.8 to 2.5 percent, indicating the use of high absorption aggregates. The combination of these absorptive aggregates and the relatively short time between production and laydown likely resulted in the aggregates not absorbing all of the asphalt binder that was absorbed during mix design (short term aging procedure). The unabsorbed asphalt binder in conjunction with the lower total aggregate surface area of the coarse-graded mixes also resulted in elevated asphalt binder film thicknesses. The end result is substantial over-asphalted mix behavior. Additionally, although not evaluated for the projects in this study, a temperature differential within the mat may have contributed to the observed tenderness.

The second probable reason for mix tenderness occurred during the Alabama Highway 78 project. This project was an overlay of a severely cracked asphalt pavement. The cracks were full depth down to a cement treated base material approximately 250-mm below. Because of the cracking, water had infiltrated the pavement. When the new mix was placed, water within the underlying pavement moved upward and turned to steam. This resulted in an increase in volume of the placed mix that was observed during construction. Recall, that portions of the pavement were patched prior to placing the new mix. In the area of the patches, no volume increases were noticed. For this project, tenderness within the mix was first noticed at around 118°C, a common temperature for the beginning of the tender zone. However, the field observations suggested that de-compaction of the mix occurred after the breakdown rolling had been completed and prior to the intermediate roller. This was verified with nuclear density gauge measurements. Therefore, this project likely did not exhibit the "tender zone."

RECOMMENDATIONS

The best recommendation when compacting a mix exhibiting the tender zone, or any HMA mix, is to pay very close attention to mix compaction temperature. Accurately knowing the mix compaction temperature is crucial to the efficient and adequate compaction of any mix, especially mixes with the tender zone present. Generally, the mix should be placed at a temperature as low as possible while still being able to achieve density. This will increase the overall mix stiffness and should result in less tenderness.

Past recommendations (3) have been made in regards to mix compaction on projects with the tender zone present. Among these recommendations was to achieve the desired density prior to the beginning of the tender zone. This may require a substantial effort by the contractor with more and heavier rollers, possibly used in an echelon pattern. Another recommendation is to compact the mix until the tender zone begins and then wait until the end of the zone to complete compaction. Many contractors have reported a gain of 1 to 2 percent in density at temperatures below 65°C. It should be noted that delaying the compaction of any mix may potentially result in an inability to achieve the target density; therefore, the decision should be based on experience with given mixes and associated weather and project conditions.

There is the possibility that a pneumatic roller can be used within the tender zone to achieve density without excessive movement of the mix. Pneumatic roller effectiveness is greatly dependent upon the proper use by contractor.

Further research should be conducted to evaluate the concept of excessive effective asphalt content due to lack of time for complete binder absorption by a highly absorptive aggregate. Complete asphalt absorption may not take place until moisture is driven out from an absorptive aggregate. The resulting excessive effective asphalt binder can contribute to the tender mix problem. This research would entail measuring the Rice specific gravity and mixture moisture contents during various stages of construction (mix at plant, after various storage times, at paver, etc.) Previous research by Kandhal and Koehler (6) and Musselman et al (7) has suggested that the volume of effective asphalt in a plant produced mix decreases with time. A study of this nature may lead to various recommended mix storage times prior to placement based upon aggregate absorptive characteristics.

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LIST OF TABLES

Table 1 Project Information

Mix Property	Project				
	Alabama Highway 157	Alabama Highway 78	Florida Interstate 10	Florida Highway 301	Mississippi Highway 49
N_{design} Gyrations	106	100	96	96	96
Coarse Aggregate	40% LMS (AL) 22% Slag	LMS	67% LMS (AL)	67% LMS (South FL)	80 % Gravel
Fine Aggregate	9% Sand 28% Slag Scrn. 1% Baghouse Fines	LMS Scrn.	33% LMS Scrn.	13% LMS Scrn.	9% Sand
RAP, %	None	15	None	20	10
Asphalt Grade	PG 67-22	PG 76-22	AC-30	AC-30	PG 76-22
Asphalt, %	4.9	4.5	6.5	7.0	6.2
Modifier Type	None	SBR, SBS	None	None	SBS
Liquid Anti-strip	None	None	0.75 %	0.75%	1.5%, 1% Lime
Ambient Temp, °C	18 - 21	16	32 - 35	29 - 32	27 - 29
Production Temperature, °C	149	168	155	155	160
Tack Coat	AC-10	RS-1	RS-1	RS-1	RS-1
Paver Type	Roadtec RP-30	N/A	Blaw-Knox PF3200	Blaw-Knox PF3200	CAT AP1000 w/CAT WE601B
Breakdown Rolling	CAT CB634C 2 Passes Max. Amplitude and Frequency 146 - 110°C	N/A	Ingersoll Rand DD130 ~ 2-3 Passes ~ Max. Amplitude and Frequency 143 - 107°C	Ingersoll Rand DD110 2-3 Passes Max. Amplitude and Frequency 146 - 107°C	Ingersoll Rand DD130 ~ 4-5 Passes ~ Med. Amplitude and Max Frequency 146 - 118°C
Intermediate Rolling	None	N/A	Ingersoll Rand DD110 2 Passes Max. Amplitude and Frequency 107 - 88°C	Ingersoll Rand DD110 2-3 Passes Max. Amplitude and Frequency 107 - 88°C	None
Finish Rolling	Hypac C764B 2 -3 Passes Static < 60°C	N/A	CAT CB634C 2-3 Passes Static < 60°C	Hypac C778B 3 Passes Static < 60°C	Hypac C778B 3 Passes Vibratory > 66°C, Static < 66°C
Tender Zone Temp. Range, °C	110 - 60	116 - 82	88 - 60	88 - 60	107 - 66

Note: All mixes are 12.5 mm nominal maximum size placed at a lift thickness of 50-mm except Hwy 78 which was a 19.0 mm NMS and placed 63-mm thick, N/A - Not Available

Table 2 Project Gradation and Volumetric Results

Sieve Size (mm)	Alabama Highway 157		Alabama Highway 78[1]	Florida Interstate 10		Florida Highway 301		Mississippi Highway 49	
	Percent Passing								
	Design	Actual	Actual	Design	Actual	Design	Actual	Design	Actual
25.0	-	-	100	-	-	-	-	-	-
19.0	100	100	95.6	100	100	100	100	100	100
12.5	96	93.8	80.4	91	94.1	98	96.9	96	97.2
9.5	79	75.0	63.1	79	87.3	89.9	91.9	89	91.7
4.75	45	41.6	34.3	45	48.0	55	58.4	61	65.2
2.36	32	30.0	25.7	28	24.4	28	28.3	41	42.1
1.18	25	22.9	20.8	20	20.0	22	22.3	29	29.9
0.6	19	17.3	14.9	15	16.4	18	18.3	22	22.6
0.3	11	11.0	7.7	10	12.4	12	14.4	13	14.5
0.15	6	6.5	5.2	4	8.5	7	9.7	8	9.7
0.075	3.4	4.3	3.9	3.5	6.3	4.8	6.3	6.1	7.8
Asphalt Content, %	4.9	4.9	4.3	6.5	6.3	7.0	7.3	6.2	6.3
VMA, %[2]	14.5	16.2	13.2	14.0	13.4	14.8	14.8	14.1	14.7
Air Voids, %	4.0	6.4	5.3	4.0	4.9	4.0	5.3	4.0	4.3
$\%G_{mm}$ at $N_{initial}$	87.2	84.7	87.2	85.8	83.4	84.3	83.2	N/A	87.2
VFA, %	72.4	60.5	59.6	71.4	63.4	73.0	64.4	71	70.7
Film Thickness (μ)	10.6	9.2	9.6	12.8	9.0	9.5	9.5	8.9	7.5
$Dust/AC_{eff}$	0.82	1.05	1.18	0.80	1.40	0.94	1.17	1.30	1.63
Mix Design Asphalt Binder Abs. (%)	0.8		1.0	2.1		1.9		1.5	

1 Design Values Not Available
2 VMA Values Based on G_{sb}

Table 3 Asphalt Binder Testing Results Before and After Steam Stripping

Project ID	DSR, G*/sinδ (kPa)		DSR (RTFO), G*/sinδ (kPa)		DSR (RTFO + PAV), G*sinδ (kPa)		BBR (RTFO + PAV)			
							S, (MPa)		m	
	Before	After	Before	After	Before	After	Before	After	Before	After
FL 301	1.597	1.602	3.661	3.489	2796	3099	158	149	0.344	0.338
FL I-10	1.762	2.062	3.878	3.914	2713	2627	141	145	0.373	0.363
MS 49	1.182	1.574	2.637	3.006	1148	1225	117	107	0.320	0.327
AL 157	1.553	1.621	3.798	3.902	1739	1698	48	52	0.341	0.344

List of Figures

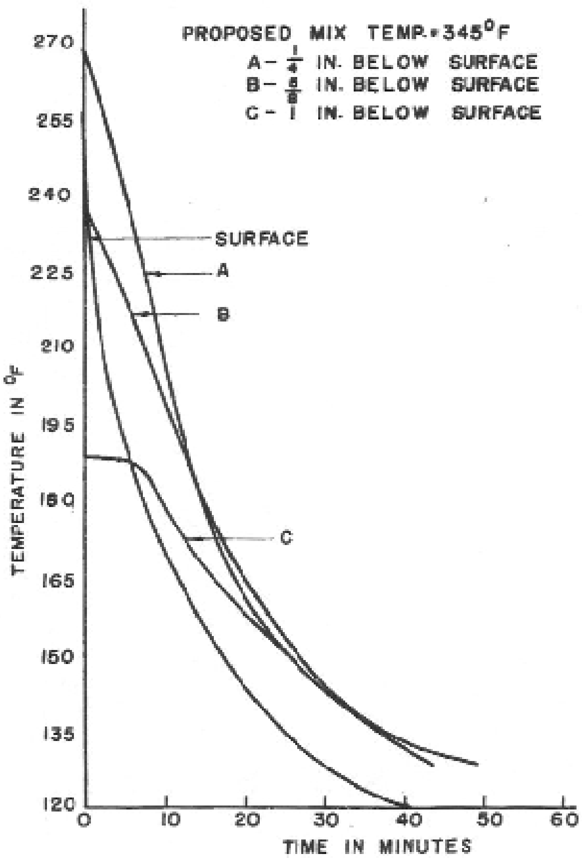

Figure 1 Differential Cooling Within an HMA Lift (4)

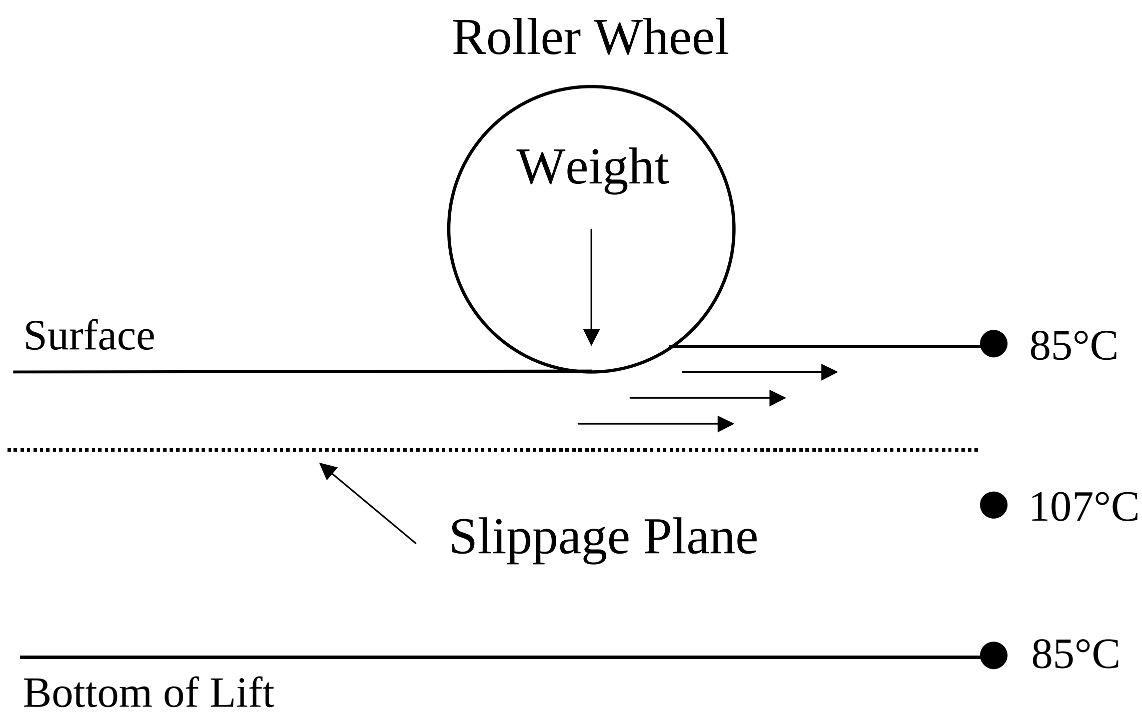

Figure 2 Roller Wheel Action on a Differentially Cooled Lift